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MEMORANDUM

Subject: Progress Report
ULI: FY13 Q3 Progress Report (4/1/2013–6/30/2013)

This document provides a progress report on the project "Advanced Digital Signal Processing" covering the period of 4/1/2013–6/30/2013.

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Advanced Digital Signal Processing for Hybrid Lidar

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Presented by:
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Outline

- Background and Objectives
- Approach and Challenges
- Light Propagation in Water
- Progress
  - New ranging technique
  - New backscatter reduction technique
- Summary

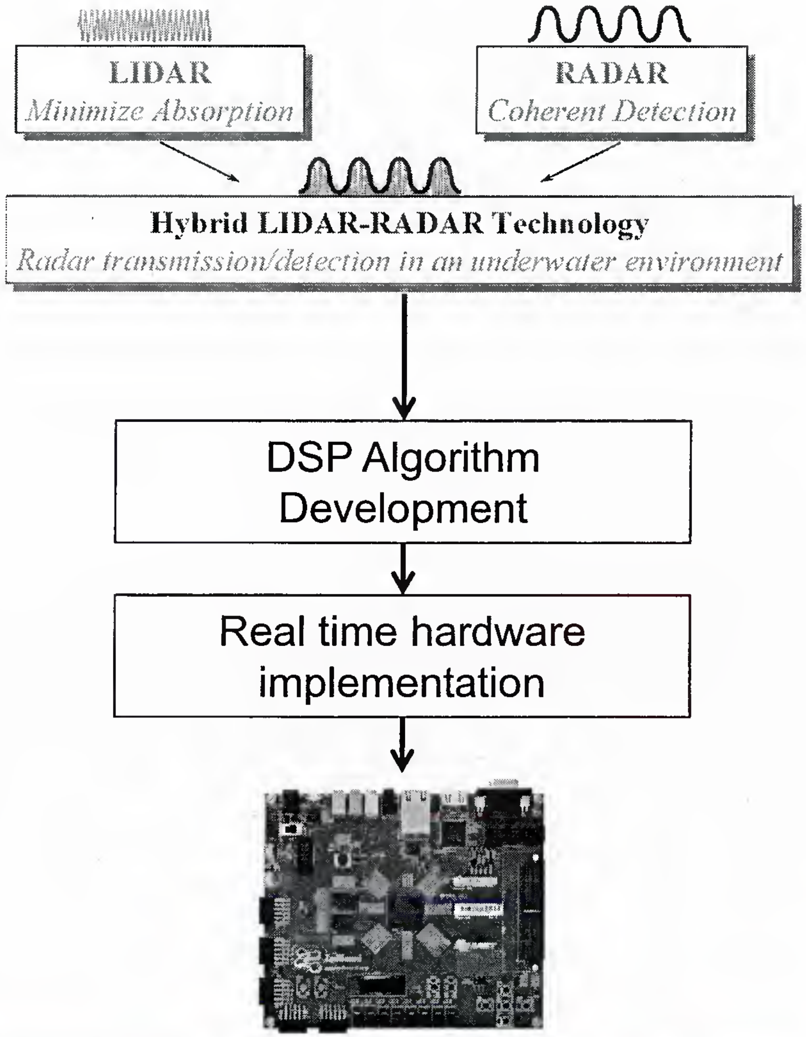
Background and Objectives

Background: The Navy uses hybrid lidar-radar for underwater detection, ranging, communications, and imaging.

- Modulate intensity of lidar laser signal with radar (RF) waveforms
- Recover radar waveform from received lidar optical signal
- Apply coherent detection and other radar techniques to process received signal.

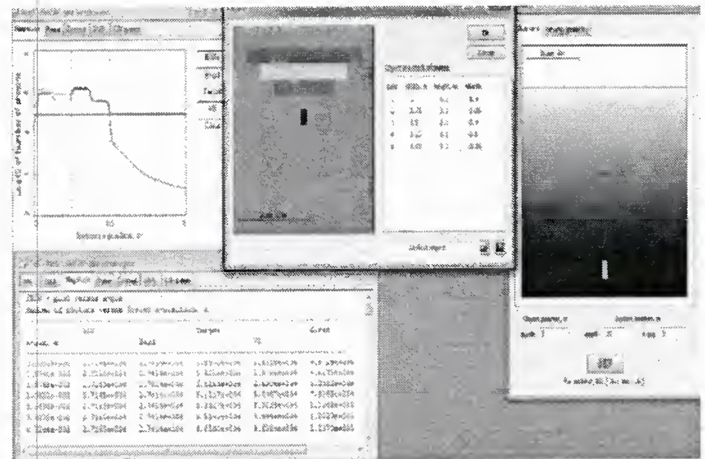
Objectives: Enhance hybrid lidar-radar performance:

- Develop and evaluate various digital signal processing (DSP) algorithms that will enhance hybrid lidar-radar performance in a variety of underwater environments.
- Implement algorithms via DSP hardware:
  - dynamically reconfigured via software (accomplish multiple missions with a single sensor)
  - real-time processing
  - reduced loss/temperature sensitivity

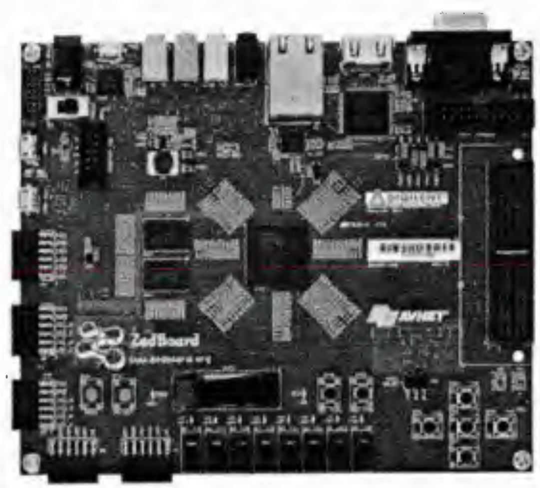


Approach and Challenges

Rangefinder



Xilinx Zynq FPGA Platform



Approach:

- Leverage algorithms that are widely used in radar and wireless communications
  - Spatial filtering
  - Frequency domain reflectometry
  - Blind signal separation

Challenges:

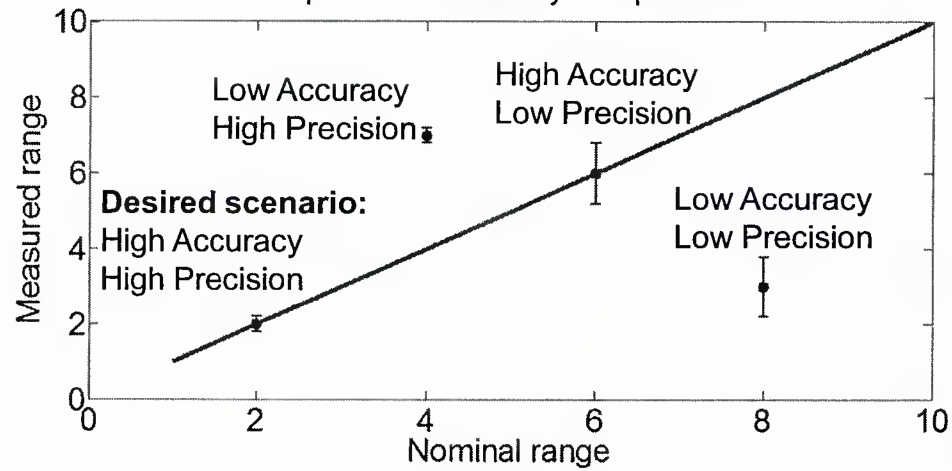
- The underwater propagation channel is very different than the above-water environment
  - Use an underwater (UW) optical propagation model, Rangefinder, to generate simulated data to test DSP algorithms
- Many COTS DSP hardware platforms (*e.g.* software defined radios) are suitable for above-water radar communications but lack performance for UW light detection and ranging
  - Utilize FPGAs tailored for application

Performance Goals

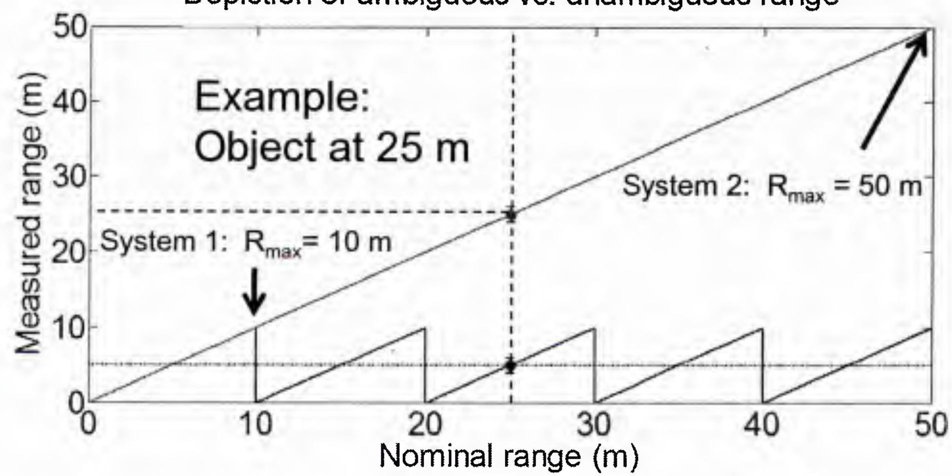
Simultaneously achieve:
high range resolution, range accuracy, range precision, and unambiguous range

1. Range resolution
   - Indicates ability to resolve closely spaced targets
2. Range accuracy
   - Indicates how close measurements are to the true range value
3. Range precision
   - Indicates how closely multiple measurements are clustered together
4. Unambiguous range
   - R_{max} indicates maximum distance at which true range is determined with no ambiguity

Depiction of accuracy and precision



Depiction of ambiguous vs. unambiguous range

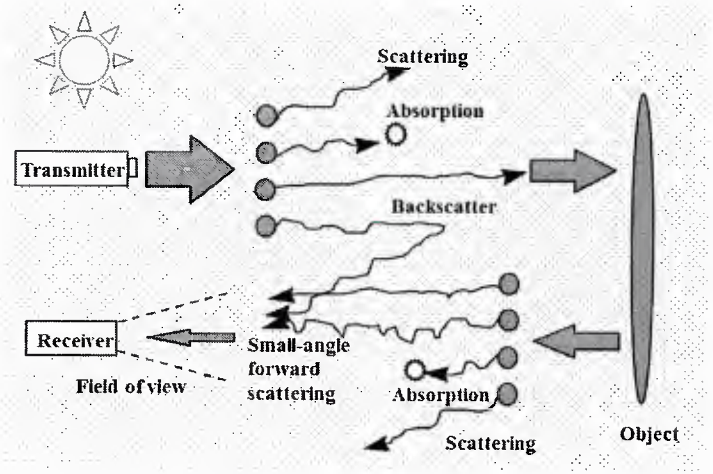


Progress and Activity

- Project start: June 2011
- Year 1
  - Participated in ONR NREIP program at NAVAIR
  - Assisted with water tank experiments
  - Characterized software defined radios
  - Identified, validated new lidar backscatter reduction technique: spatial filter
- Year 2
  - Participated in ONR NREIP program at NAVAIR
  - Spatial filter experiments
  - Identified new ranging technique: frequency-domain reflectometry
  - Identified new backscatter reduction technique: blind signal separation
- Summer 2013 (planned)
  - Participate in ONR NREIP program at NAVAIR
  - Thorough evaluation of new techniques
  - Validate new techniques with laboratory experiments
- Publications
  - "Underwater Laser Rangefinder," Proceedings of SPIE 2012, Ocean Sensing and Monitoring IV, Volume 8372
  - "Techniques to enhance the performance of hybrid lidar-radar ranging systems," Proceedings of MTS/IEEE Oceans 2012
  - "Technique to Extend Unambiguous Range of Hybrid Lidar-Radar Systems," Proceedings of MTS/IEEE Oceans 2013 (submitted)

Light propagation in water

- Absorption decreases the total signal level at the receiver
- Scattering degrades image contrast, resolution, and reduces range accuracy



Absorption vs. Scatter-Limited Performance

Absorption-limited detection – more light, more range

Scatter-limited detection – more light, more 'clutter'

- Although absorption and scattering are two separate phenomena, their effects on water conditions are often combined together into a single parameter, the attenuation coefficient c (units: m^{-1})
- Beam attenuation in water follows an exponential decay law, where cz is the number of attenuation lengths (a.l.) :

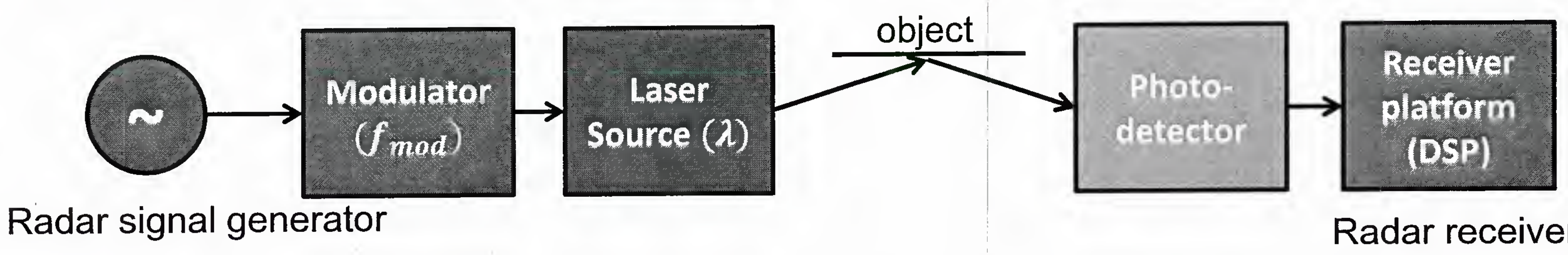
$$P(c, z) = P_0 \, exp(-cz)$$

After traveling one attenuation length, the optical beam is attenuated by a factor of $1 - \frac{1}{e} \approx 63.21\%$

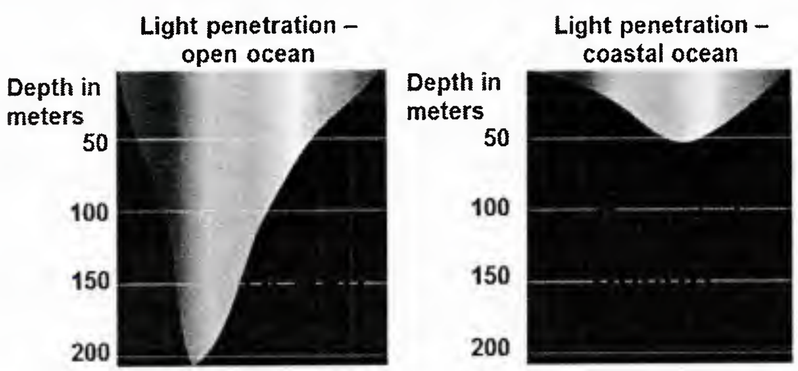
- We are focusing on enhancing performance in scatter-limited scenarios

Three ways to improve performance in backscatter-limited scenarios

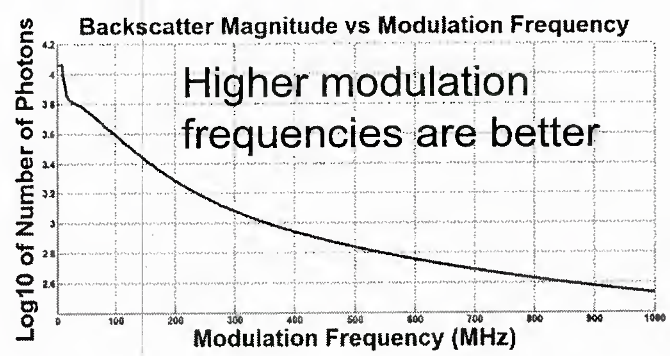
Simplified lidar-radar system



1. Wavelength Selection (λ)

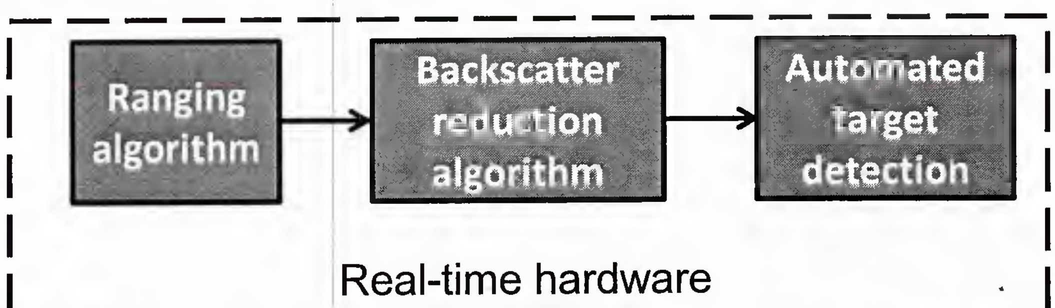


2. Modulation Frequency Selection (f_{mod})



3. Digital Signal Processing (DSP)

Our focus is to apply DSP algorithms to the receiver platform in order to **improve performance by processing the received signal.**



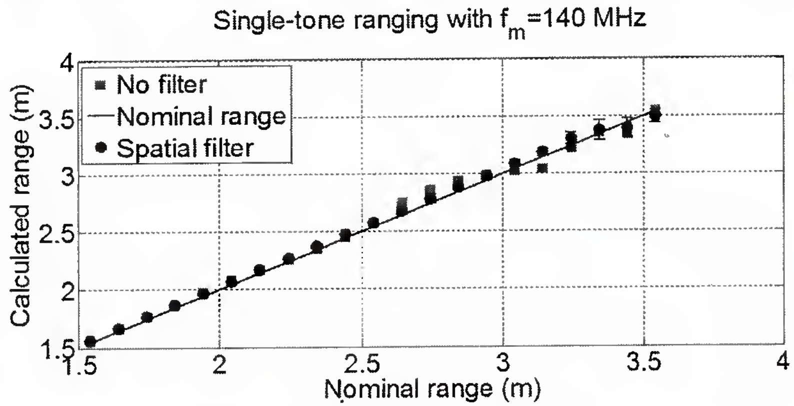
Technical Results Overview

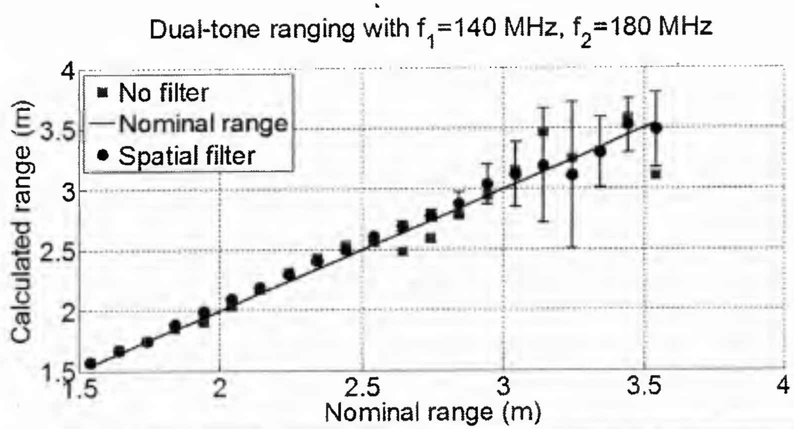
Goal: automatically detect a target and calculate range **without** any *a priori* knowledge

Ranging	Backscatter reduction	Target detection
Ranging Algorithm →	**Backscatter Reduction Algorithm** →	**Automatic Target Detection Algorithm**
Approaches:		
1. Single/Dual Tone	Spatial Filter	Phase to Range
2. Frequency Domain Reflectometry	Blind Signal Separation	Peak Detection

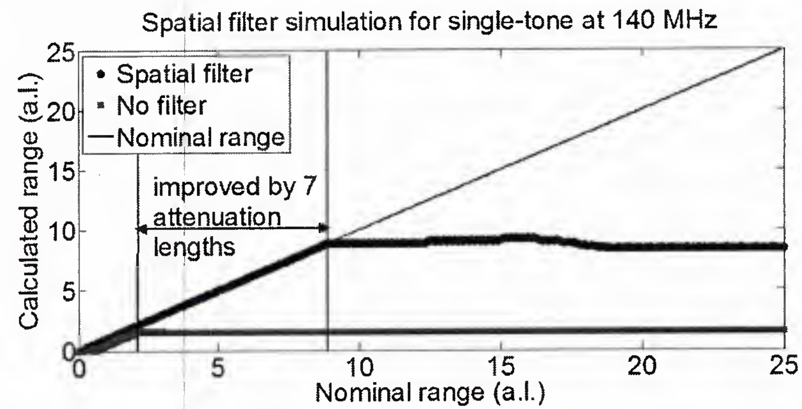
Approach #1: Spatial Filter Results

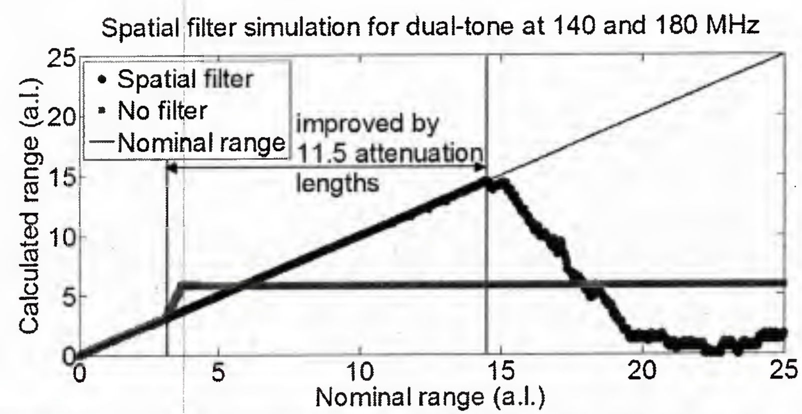
Results from 2012 Experiments, $c = 2.5\ m^{-1}$





Simulation of Theoretical Performance





Range Algorithm	Unambiguous range	Range precision	Range Improvement with Spatial Filtering
Single-tone 140 MHz	0.80 m	2.65 cm	**7 a.l.**
Dual-tone 140, 180 MHz	2.81 m	12.40 cm	**11.5 a.l.**

Technical Results Overview

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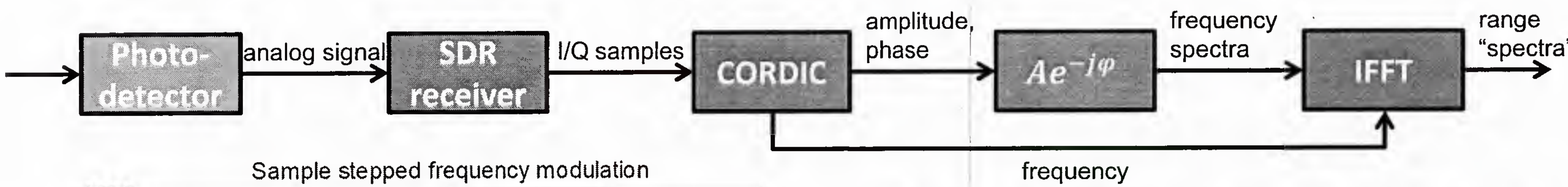
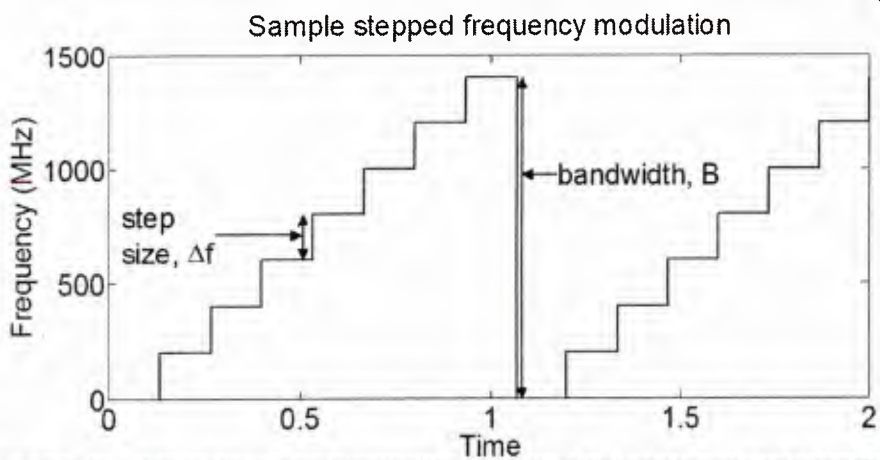
2. Frequency Domain Reflectometry	Blind Signal Separation	Peak Detection

Approach #2 Ranging Algorithm: Frequency-Domain Reflectometry (FDR)

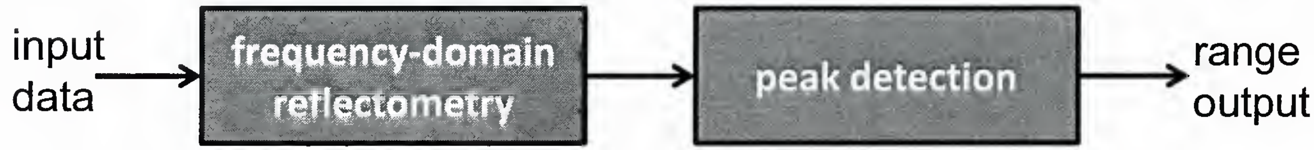
- FDR is a stepped frequency technique developed to detect faults in RF and fiber optic cables
- Small step size can lead to large unambiguous range performance
- Requires a large bandwidth to achieve comparable precision to CW methods



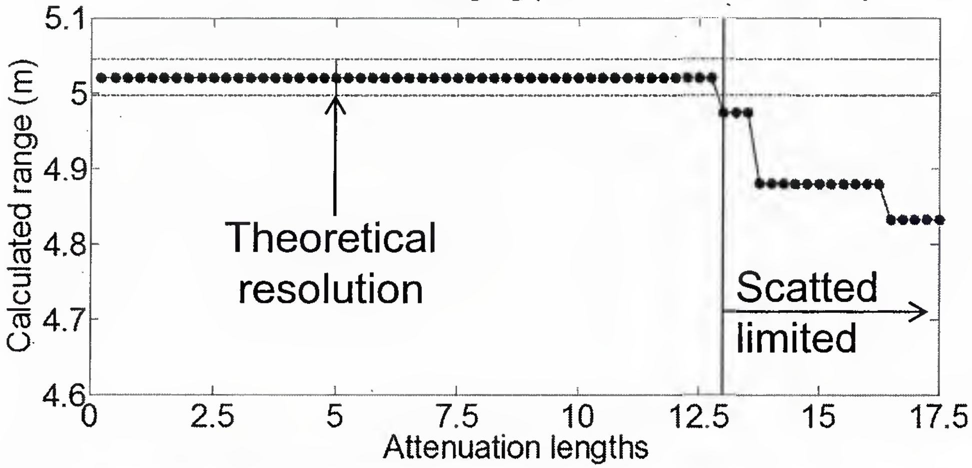


Parameter	Equation
Unambiguous range	$R_{max} = \frac{\nu}{2\Delta f}$
Range precision	$\delta R = \frac{\nu}{4B}$

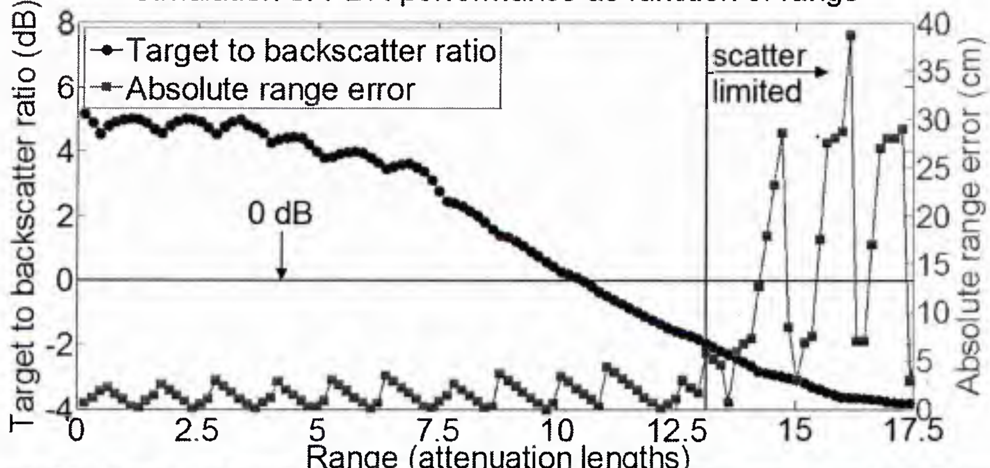
Approach #2: FDR Simulated Results with Automated Target Detection



Simulation of FDR ranging performance vs. turbidity



Simulation of FDR performance as function of range



Simulation: Fixed target range, varying turbidity.

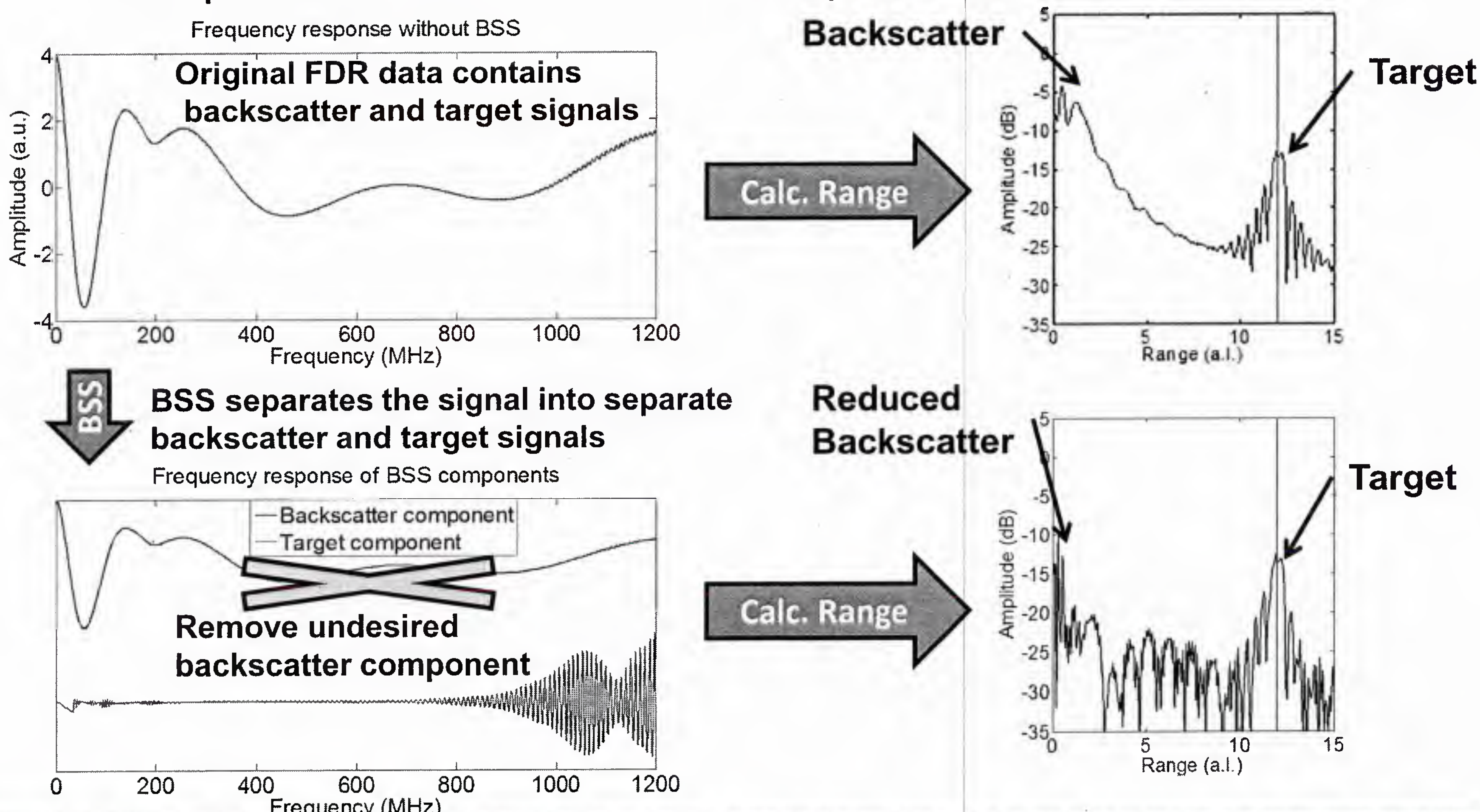
- BW = 1.2 GHz;
- Δf = 1.17 MHz;
- δR = 4.69 cm;
- R_{max} = 48.0 m
- No backscatter reduction processing

Results: automated target detection works to 13 a.l. corresponding to target-to-backscatter ratios of -2 dB

Next step: apply blind signal separation to reduce backscatter

Approach #2: Blind Signal Separation for Backscatter Reduction

- Photons reflected from objects and backscatter in the scene are recorded as a single "mixed" lidar return
- Applying blind signal separation (BSS), the target and scatter components of the return can be separated



Blind Signal Separation (BSS) Math Overview

- Objective: Separate observations of several signals into the independent signal components based on their statistics

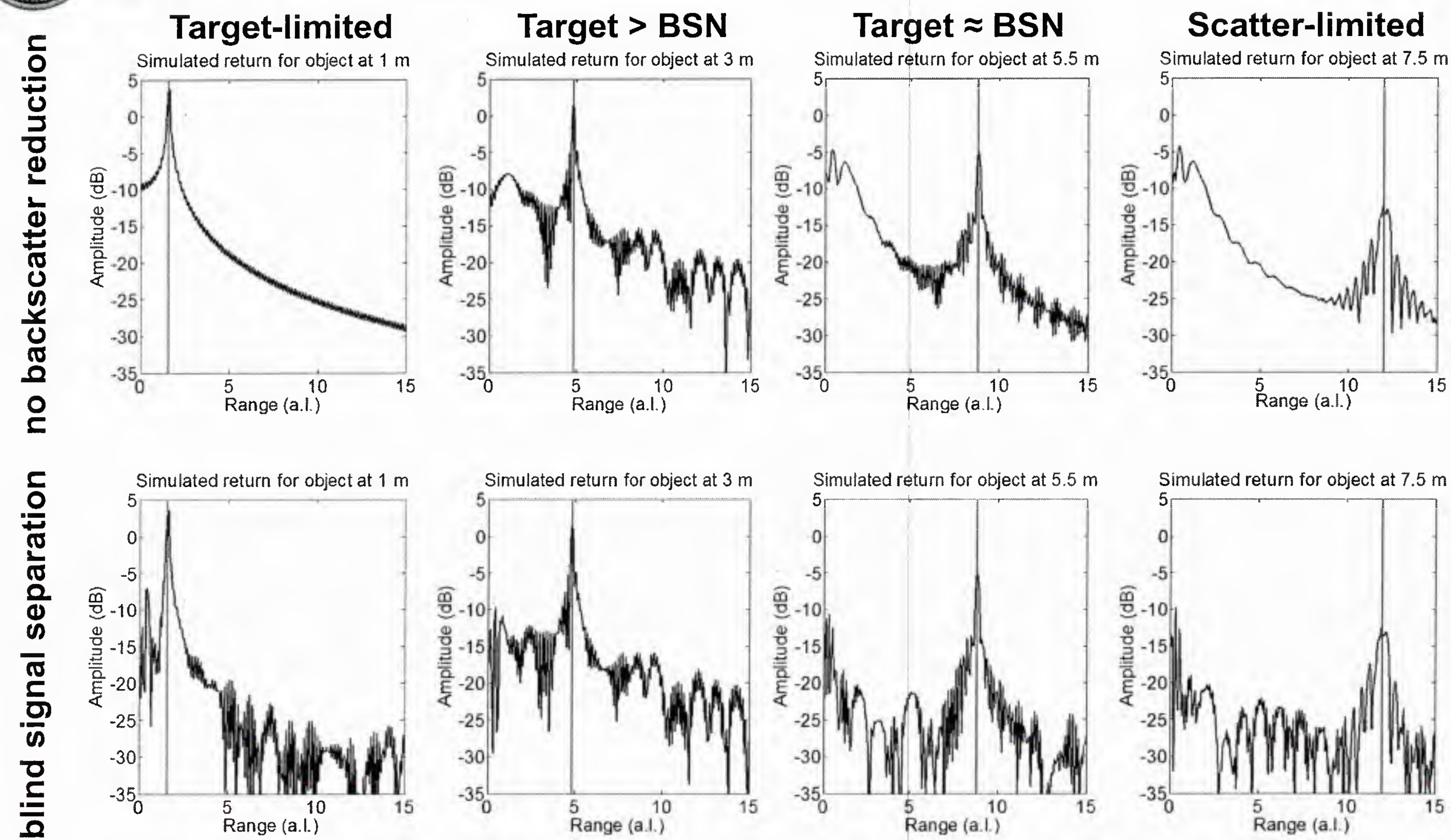
- Model: $X = AS$

  X: observation matrix, A: "mixing" matrix, S: source matrix

- Methodology: Select a statistical property. Adaptively learn a weight matrix $W \approx A^{-1}$ based on X. W should maximize separation based on the desired statistical property. At convergence, source components are estimated as $\hat{S} = WX \approx A^{-1}X$

- Challenges:
  - Choice of statistical property
  - Choice of convergence criteria
  - Estimation of number of sources
  - Choice of number of observations
  - Computational complexity

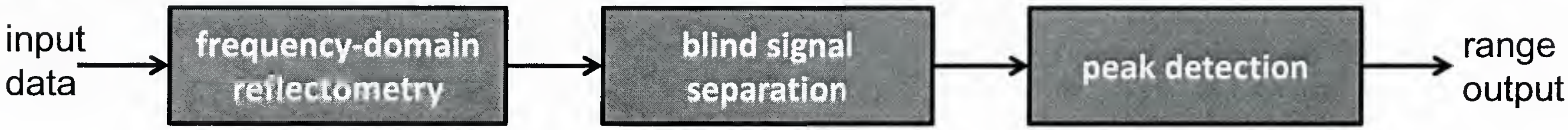
Approach #2: FDR Simulated Results with and without Backscatter (BSN) Reduction

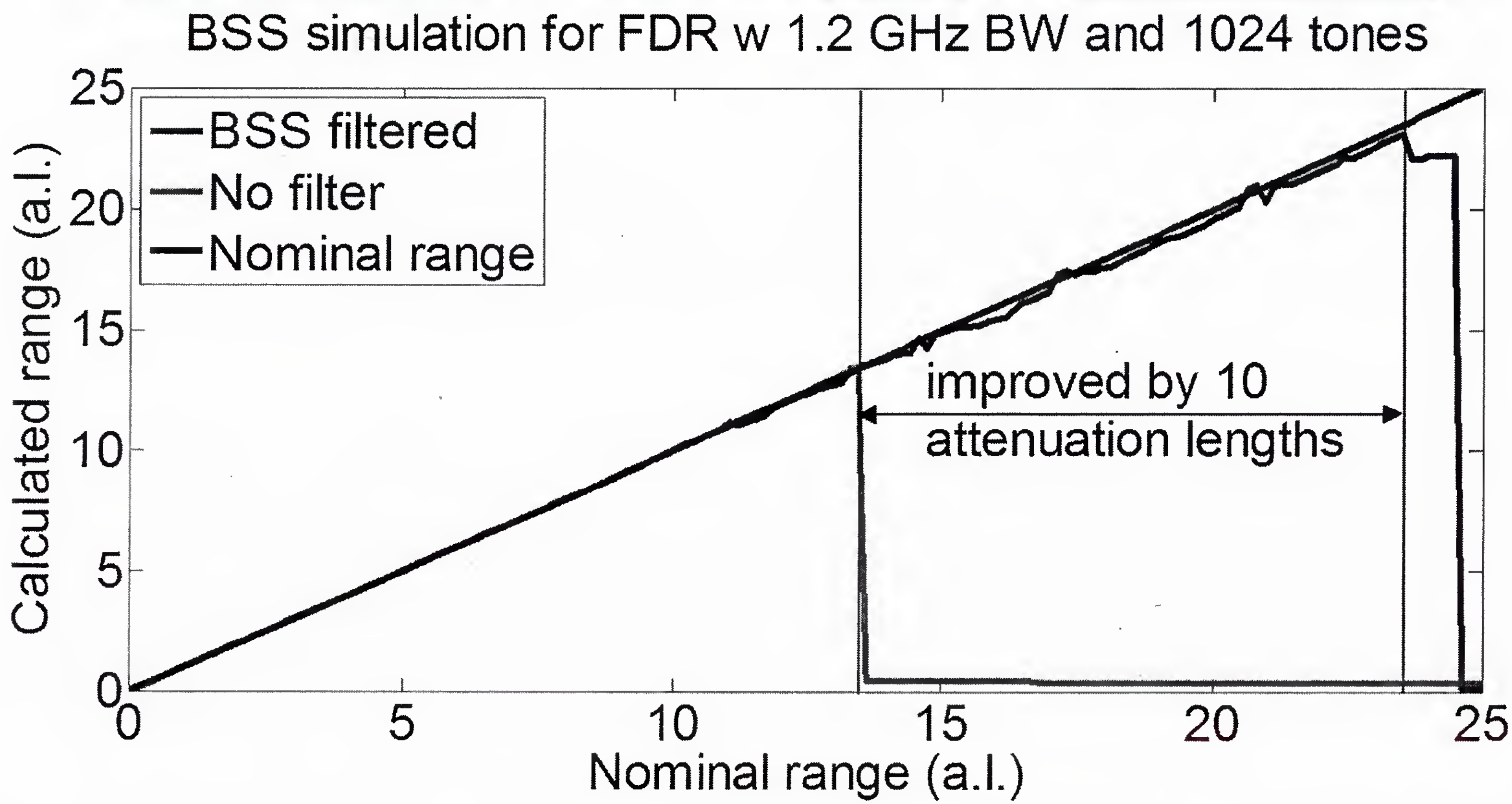


Green lines indicate actual target position

Range bin size: 9.38 cm; Turbidity: $c = 1.6\, m^{-1}$

Approach #2: FDR with BSS and Automated Signal Detection





$c = 1.6\ m^{-1}$; BW = 1.2 GHz; Δf = 1.17 MHz

δR = 4.69 cm; R_{max} = 48.0 m

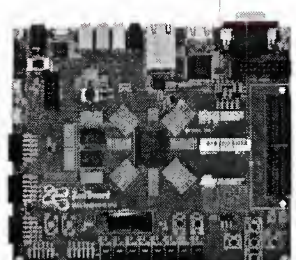
Real-Time Implementation

- Several basic building blocks have been implemented on real-time DSP hardware:
- Baseband demodulation
  - Decomposes RF signal into two orthogonal vectors
- CORDIC (COordinate Rotation DIgital Computer)
  - Given two vectors, finds the magnitude and phase angle of the resultant vector
  - The phase angle can be used to calculate range
- Instantaneous frequency demodulator
  - Calculates the frequency of the input signal

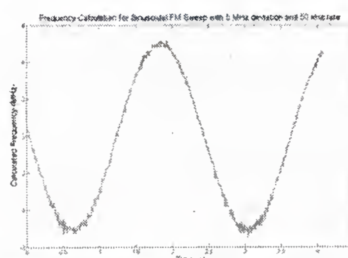
Example: demodulation of sinusoidal frequency modulated signal

1. System design

2. Implementation



3. Calculation



Technique Comparison

Approach 1

Single- and Dual-Tone Ranging

+ short dwell time
+ very high precision
– single range result
– tradeoff between f_{mod} and R_{max}

Spatial Filter

+ computationally simple
+ single parameter
– logistically complicated
– implementation dependent on f_{mod}

Approach 2

Frequency-Domain Reflectometry

+ large unambiguous range
+ "range spectra"
– large bandwidth
– long dwell time

Blind Signal Separation

+ logistically simple
+ implementation independent of f_{mod}
– computationally complicated
– many parameters

Summary

- Significant progress has been made in developing a digital signal processing approach to enable hybrid lidar-radar ranging systems to perform automatic target detection:
  - Ranging: frequency-domain reflectometry technique provides large unambiguous range
  - Backscatter reduction: blind signal separation technique is able to separate the target and scatter returns
  - Target detection: simple peak detection algorithm is able to automatically detect target position

- Planned work
  - Experiments planned for summer 2013 to test performance of new technique as a function of range and turbidity
  - Continue to perform experiments with spatial filter method
  - MTS/IEEE Oceans Conference presentation in Fall 2013
  - Explore more sophisticated target detection algorithms that combine FDR and signal-tone approaches to improve precision
  - Develop real-time versions of each technique

Background Slides

Frequency-Domain Reflectometry (FDR) Overview

1. Transmit stepped frequency sweep with N tones
2. For each frequency f_i, record magnitude A_i and phase φ_i
3. Construct complex vector $S_i = A_i \exp(j\varphi_i)$
4. Calculate inverse Fourier transform of S_i: $s(t) = \frac{1}{2\pi} \int S(f) \exp(2\pi f t)\, df$
5. Peaks appearing in the time-domain can be converted to range by multiplying by the speed of light

Frequency-Domain Reflectometry (FDR) Range Equation Derivation

- FDR range equations are based on applying Nyquist sampling theory in the frequency-domain
- Unambiguous range:
  - Frequency sample spacing: Δf
  - Maximum sampling time: $t_{max} = \frac{1}{\Delta f}$
  - Convert to range: $R_{max} = \frac{\nu}{2} t_{max} = \frac{\nu}{2\Delta f}$
- Range precision:
  - Time bin size: $\delta t = \frac{1}{2N} t_{max} = \frac{1}{2N\Delta f} = \frac{1}{2B}$
  - The factor of one-half is needed because the maximum error is half the size of a bin
  - Convert to range: $\delta R = \frac{\nu}{2} \delta t = \frac{\nu}{4B}$

Blind Signal Separation (BSS) Math Overview

- Objective: Separate observations of several signals into the independent signal components based on their statistics

- Model: $X = AS$
  X: observation matrix, A: "mixing" matrix, S: source matrix

- To separate components based on variance:

1. Calculate sample covariance matrix $C = X^T X$
2. Apply singular value decomposition:
$$X = USV^T$$
   U: projection of X onto eigenvectors of C, S: diagonal matrix of eigenvalues of C, V: eigenvectors of C
3. Remove undesired components by "zeroing-out" columns of U and corresponding rows of S to obtain U_0 and S_0
4. Calculated filtered observations as $X_{filt} = U_0 S_0 V^T$